# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
December 21, 1995

**3. REPORT TYPE AND DATES COVERED**
Final Technical Report 3/1/93-10/31/95

**4. TITLE AND SUBTITLE**
Identification and Active Control of Nonlinear Fluid/Structure Interactions

**5. FUNDING NUMBERS**
AFOSR Grant
F49620-93-1-0198

**6. AUTHOR(S)**
H.T. Banks

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Center for Research in Scientific Computation
North Carolina State University
Campus Box 8205
Raleigh, NC 27695-8205

**8. PERFORMING ORGANIZATION**
AFOSR-TR-96
0308

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Dr. Marc Q. Jacobs
AFOSR/NM
110 Duncan Ave., Suite B115
Bolling AFB, DC 20332-0001

**AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

**12a. DISTRIBUTION / AVAILABILITY STATEMENT**
Approved for public release; distribution unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*
The research efforts involved theoretical, computational, and experimental research in the general area of control of structures and nonlinear flow/ structure interactions. The work, pursued in an integrated, multidisciplinary approach, involved basic research on modeling, identification, control, and computation in (i) flow control (ii) smart material structures (iii) control of nonlinear fluid/structure interaction models (iv) fluid flow in a vertical chemical vapor deposition reactor, (v) pharmacokinetics dynamics and (vi) computational electromagnetics. Major acheivements include the development, implementation and experimental validation of (a) feedback control algorithms for use in vibration suppression in smart structure active noise suppression and (b) noninvasive damage detection algorithms based on routine structural vibration responses.

19960520 069

**14. SUBJECT TERMS**

**15. NUMBER OF PAGES**

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

# Final Technical Report
on

# Identification and Active Control of Nonlinear Fluid/Structure Interactions

for the period

March 1, 1993 - October 31, 1995

**AFOSR F49620-93-1-0198**

Program Manager:

Dr. Marc Q. Jacobs
AFOSR/NM
110 Duncan Ave., Suite B115
Bolling AFB, DC 20332-0001

prepared by:


Dr. H.T. Banks
Center for Research in Scientific Computation
Box 8205
North Carolina State University
Raleigh, NC 27695-8205
email: htbanks@crsc1.math.ncsu.edu
FAX: 919-515-3798
Phone: 919-515-3968


December 21, 1995

# Executive Summary

The research efforts involved theoretical, computational, and experimental research in the general area of control of structures and nonlinear flow/structure interactions. The work, pursued in an integrated, multidisciplinary approach, involved basic research on modeling, identification, control, and computation in (i) flow control (ii) smart material structures (iii) control of nonlinear fluid/structure interaction models (iv) fluid flow in a vertical chemical vapor deposition reactor, (v) pharmacokinetics dynamics and (vi) computational electromagnetics. Major acheivements include the development, implementation and experimental validation of (a) feedback control algorithms for use in vibration suppression in smart structure active noise suppression and (b) noninvasive damage detection algorithms based on routine structural vibration responses. Detailed descriptions of the efforts and results can be found in the readily available publications listed in this report. Those listed as CRSC-TR are technical reports available upon request at the Center for Research in Scientific Computation, North Carolina State University. Investigators supported in part under this grant include H.T. Banks, K. Ito, Y. Wang, K. Black, R.C. Smith, M. Demetriou, N. Lybeck, A. Ackleh, S. Zhu, S. Ravindrin, R. del Rosario, Y. Zhang, T. Roberts, C. Musante, and H. Tran.

# 1 Flow Control

Two types of boundary control problems were investigated for the incompressible Navier-Stokes equations. The first problem is the fluid/structure interaction by an elastic boundary condition for a channel flow with sudden expansion. The idea of applying smart materials to mechanical and structural systems has been exploited in various applications. A number of promising materials with adaptive properties are being tested and used as sensor or actuator elements. For example, piezoelectric material can be used as induced strain actuators which result in a mechanical deformation. When deformed, piezos also generate a voltage that is proportional to the cummulative strain in the structure. This capability permits piezoelectric materials to be employed as sensors and actuators and combined with laws for the design of an elastic deforming wall for control in channel flow. A mathematical model including equations and boundary interface conditions for this fluid/structure interaction was developed and the well-posedness of the proposed equation based on a weak variational formulation under a Gelfand triple was established. A code was developed for numerical simulation of the fluid/structure interaction based on this mathematical formulation. The code uses the mixed-finite element method for the spatial approximation and an operator splitting method for the time integration. A class of linear feedback laws was developed for minimizing the total vorticity in a recirculation region due the sudden expansion of the channel; these laws were tested numerically. Numerical tests were carried out for open-loop and closed-loop systems under different flow conditions. These computational results validated the mathematical formulation and the feasibility of the proposed feedback control mechanisms.

The second problem studied was the Boussinesq system for thermal convection. The problem is motivated by optimal control and design for high pressure vapor transport (HPVT) reactors for epitaxial growth under open and closed reactor design. The Navier-Stokes equa-

tions are coupled with the thermal equation for energy conservation through the buoyancy force. The boundary temperature control of mixed and Dirichlet boundary types were considered for regulation of temperature and velocity field. A weak variational formulation under a Gelfand triple framework was used to establish the existence of weak solutions under very mild regularity assumptions on the boundary data and to derive the necessary optimality condition. The necessary optimality conditions played a very important role for developing and analyzing numerical optimization algorithms. In addition, numerical optimization algorithms based on the augmented Lagrangian method were developed and tested for a stationary control problem that arises in the boundary temperature control for the closed tube HPVT reactor design. Finally, the full compressible Navier-Stokes equation was analyzed theoretically and computationally in order to study the density variation effect for flow fields in HPVT reactors.

# 2 Control and Identification in Smart Materials

Investigators have continued studies of feedback control and parameter estimation in the context of piezoceramic based smart materials. Several important achievements have been realized during the past two years. The group investigated methods for non-destructive detection and location of damage in structures using a distributed parameter based methodology. These efforts on the possibility and feasibility of vibration analysis based detection of damage have resolved a number of issues that have provided controversy in the engineering community for the past 20 years. Using physically based distributed parameter models for structures, the group successfully developed and experimentally validated methods for the detection and characterization of damages such as corrosions and structural defects in elastic structures. These methods are based on routine vibration responses for the characterization of changes in fundamental geometry and physical parameters (mass density, stiffness, damping) using embedded piezoceramic sensors/actuators in a self-excitation, self-sensing structural environment. Their efforts have produced resolution and capabilities that cannot be attained with classical modal based methods that have been at the heart of controversies in the engineering community. The computational and experimental findings of the team on damage detection in elastic structures such as airfoils and aircraft fuselages has potential for significant breakthroughs in evolving technologies for on-line methods in both civilian and military application. This work, part of which has also been carried out in collaboration with scientists at NASA Langley Research Center, has major impact on and is of fundamental importance to the implementation of a smart material based technology for the routine evaluation of materials and structures for damage (due to internal as well as external stresses) during the lifetime of the structure.

The same physically based distributed parameter models for structures with embedded piezoceramics for sensing and actuating have been used as the basis for a feedback control methodology for the suppression of vibrations in mechanical systems. Based on mathematical theories for feedback control of distributed parameter systems (developed over the last decade in large part by investigators with funding from the AFOSR thrust on the control of distributed parameter systems), the team developed and implemented a computational methodology for the control of vibrations in mechanical systems and structure borne noise

in structural acoustics systems. By also developing the necessary on-line filters and compensators (to treat partial observations of the system), the team was able to implement and test this methodology on a component of a structural acoustics experimental system subject to both periodic sustained disturbances and impulse or transient disturbances. The closed loop feedback system yielded outstanding stable performance in both cases: a typical reduction of 85% was achieved in responses to sustained distrubances while typical settling times were reduced by a factor of 4 in transient responses. These experimental verifications demonstrate conclusively for the first time that a distributed parameter feedback control methodology in the context of smart material vibrations and noise suppression is not only feasible but can provide significant improvement of current engineering capabilities.

The above cited results are part of the focus of the group's research on *control and estimation of infinite dimensional dynamical systems* as they relate to (and model) systems derived from physical processes. Specifically, the group has been looking at the extensions of several finite dimensional control and estimation theories to infinite dimensional systems. The infinite dimensional systems considered were systems governed by partial differential equations, functional differential equations (delay equations) and integrodifferential equations. Specific work on the *$H^\infty$/Min-Max control of structural acoustic models with piezoceramic actuators* using only input/output information was pursued. This control methodology was an extension to infinite dimensional systems of the methodology for finite dimensional systems with state and measurement noise. More recently, members have been working on *failure detection and accommodation* of infinite dimensional dynamical systems using *model-based* fault diagnosis schemes. These schemes allowed the failures, occurring in a dynamical system, to be detected. In addition, these *model-based* schemes were capable of identifying the nature of the fault thus enabling the accommodation of the system via the design of suitable control strategies.

Several aspects of the work include:

(a) Adaptive parameter estimation: Investigators developed a unified framework for the adaptive estimation of parameters for infinite dimensional systems. A similar application to the above on-line estimation theory included the adaptive identification of parameters in a structural acoustic model with piezoceramic actuators. In this case the previous scheme was modified to account for the lack of symmetry of certain bilinear forms in the underlying beam/pressure equation. Continuing with other extensions, *nonlinear infinite dimensional dynamical systems* were considered. There, an adaptive parameter estimation scheme, modified for a nonlinear beam model with discontinuous (with respect to time and space) stiffness parameter, was considered. Theoretical and numerical results for this application-oriented extension have been presented in the published literature.

(b) Model reference adaptive control: A unified framework that included both *linear and nonlinear* infinite dimensional systems utilizing a *functional analytic setting* was developed. The proposed control law was shown to yield state convergence, i.e., the state of the plant was shown to follow the state of a reference model with the unknown parameters updated adaptively.

Since some second order systems could not be written as first order systems, a different theory for model reference adaptive control was developed. The control

laws for this case were infinite dimensional and their implementation necessitate a *finite dimensional approximation theory.* The above theory was also extended to parabolic systems with parameters (constant and functional) that varied slowly with time.

Even though the above methodology introduced a unifying framework for model reference adaptive control, it required that the input operator be the identity operator. A way to alleviate such a restriction was proposed. This adaptive controller guaranteed that the plant state tracked the reference state. An abstract framework including details of the well posedness and proofs of convergence of such a scheme is presented in the publications listed below.

(c) $H^\infty$ control of acoustic/structure interaction models: Controllers were modified to account for a *periodic noise* that entered the system. This required the solution of two "Riccati" type operator equations. These Riccati type equations were an extension of finite dimensional results in $H^\infty$ control theory. In addition to the periodic noise, the algorithm also handled *measurement and state noise* and essentially guaranteed that the noise-to-output map remained bounded in some sense. The proposed compensator for the system was infinite dimensional. Thus, for implementation purposes, a finite dimensional approximation theory was developed. In implementing this theory, the necessary software was also developed and, upon extensive testing, successful results were obtained as already indicated above.

These results were also extended to a 3-dimensional structural acoustic system (which modeled an actual experimental setup at the Acoustics Division at NASA-Langley) where the numerical aspects of the compensator implementation were considered.

(d) Fault detection and diagnosis: Many dynamical systems undergo failures and in order to accommodate their performance with the choice of a suitable controller, it is necessary to detect these failures. An attempt was made to develop an on-line scheme that would *detect the failure* in a *nonlinear cantilevered beam model.* The beam model assumed a nonlinear stiffness which depended on the curvature of the beam. The estimator successfully monitored and detected the failure in computational experiments. In addition, it identified the parameters of the nonlinear stiffness. The same scheme was applied to computations for a linear parabolic system in which the nature of the fault was not known. In computations, a proposed model-based diagnosis scheme detected the time of failure and the location and shape of the fault, which in this case was modeled by a perturbation of the diffusivity parameter acting on part of the spatial domain.

# 3 Pharmacokinetic Dynamic Modeling

Investigators have collaborated with scientists at the Armstrong Laboratory, Brooks AFB on the modeling of hepatic dispersion of TCDD. The chemical 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) is one of the most extensively studied chemicals in recent years. There is

widespread fear that exposure to even a small dosage of dioxin could lead to adverse health effects. This chemical has been of particular concern to VietNam veterans because of its presence in the herbicide Agent Orange which was used for defoliation during the VietNam war. Agent Orange is a 1:1 mixture of 2,4-D (dichlorophenoxyacetic acid) and 2,4,5-T (trichlorophenoxyacetic acid). 2,3,7,8-TCDD forms as a byproduct in the manufacture of 2,4,5-TCP (trichlorophenol) which is needed to produce the bactericide hexachlorophene and phenoxyherbicides like 2,4,5-T and Silvex.

Due to the high lipid solubility of dioxins, these compounds are easily absorbed by the body, and are probably transported throughout the body in association with lipoproteins and other transport proteins in the blood. In most animal studies, TCDD is transported to and accumulates in the liver and adipose tissue. Elimination of lipophilic chemicals such as dioxins is by metabolic conversion of the chemical to more water soluble metabolites. Therefore, an understanding of hepatic dioxin elimination is an important determinant of dioxin and metabolite levels in the body.

There are two commonly used models to describe the elimination of substances by the liver. One is the well-stirred model and the other is the parallel-tube model. These two models are equivalent to the perfectly mixed and plug flow reactors used in chemical reaction engineering. Comparison studies including experimental evidence comparing the well-stirred model with the parallel-tube model have shown no concensus preference. In the studies underway, investigators are developing another model for hepatic elimination, the dispersion model. This model was first introduced by Roberts and Rowland (*Michael S. Roberts and Malcolm Rowland, "A Dispersion Model of Hepatic Elimination: 1. Formulation of the Model and Bolus Considerations", J. of Pharmacokinetics and Biopharmaceutics, Vol. 14, No. 3, 227-260, 1986*). This more general dispersion model is based on the residence time distribution of solutes in the liver and on hepatic physiology. In the model developed by Roberts and Rowland, metabolism and transport are operating linearly and TCDD binding to proteins in the liver are neglected. In the current study, metabolic processes are characterized by Michaelis-Menten enzyme kinetics (nonlinear) and TCDD binding to two proteins in the liver: a non-inducible high-affinity, low capacity cytosolic protein known as the Ah receptor, and an inducible low-affinity, high-capacity microsomal protein are included. The mathematical model describing the concentrations of solute in the blood and of unbound solute in hepatocytes is given by a nonlinear coupled system consisting of a convection-diffusion type equation and an algebraic constraint. A new model has been developed and investigators are currently developing an approximation scheme based on the finite element discretization for the numerical simulation of the hepatic elimination model. Simulation studies to unify the model will be carried out with continuing AFOSR funding from another grant. This work will be pursued in collaboration with Armstrong Lab scientists.

# 4 Computational Electromagnetics

Collaborative efforts with researchers at Armstrong Labs, Brooks AFB on computational electromagnetics with special emphasis on identification and control were begun. One project, which is continuing with other AFOSR support, involved the modeling of microwave probes in tissue and solids. Time domain algorithms for identification of dielectric constants

and dispersion from reflected signals have been developed and are currently being tested computationally.

A second project involved computational algorithms for inverse scattering in layered electromagnetically dispersive media. An algorithm, based on Green's function techniques, for oblique incidence waves was formulated and computationally validated using a long established method due to Redhefter. Additional work on asymptotic analysis of these algorithms was pursued.

# 5 Interactions and Transitions

The efforts supported by this grant have led to significant interaction and collaboration with non-academic scientists. These interactions involved both consultative collaborations and transitions. Among these are:

(a) Scientific collaborations on inverse and control problems in electromagnetic wave applications. Armstrong Labs, Brooks AFB.

Dr. Yun Wang, (August, 1994) and (October 30 - November 1, 1994); Dr. R. Albanese, Dr. Yun Wang (January 19-23, 1995); Dr. Yun Wang and Dr. Jeff Blaschak (Feburary 22-24, 1995); Dr. Yun Wang (April 27-29, 1995); Dr. Yun Wang (July 13-14, 1995); Dr. Yun Wang (August 28-30, 1995).

(b) Scientific collaborations on modeling of dioxin transport, Armstrong Labs, Brooks AFB.

Dr. R. Albanese (January 19-20, 1995).

(c) Scientific collaboration on modeling and computation of smart material vibration suppression in structures, Phillips Lab, Kirtland AFB.

Capt. Jeanne Sullivan, Dr. Alok Das (July 31- August 1, 1995).

(d) Transitions with Thomas Lord Research Center, the Lord Corporation (Dr. Lynn Yanyo, Dr. Beth Muñoz) Enabling research includes development of computational methodology and software packages for inverse problems involving distributed parameter systems. Application is to the modeling and design of rubber based elastomers to be used in automotive, aircraft, heavy equipment vibration suppression devices.

# 6 Publications Supported in Part Under this Grant

1. H.T. Banks and B.B. King, Modeling and control of a nonlinear beam in *Vibration and Control of Mechanical Systems* (C.A. Tan and L.A. Bergman, eds.), ASME, New York, DE **61** (1993), pp. 35-41.

2. H.T. Banks, Y. Wang, D.J. Inman, and J.C. Slater, Approximation and parameter identification for damped second order systems with unbounded input operators, CRSC-TR93-9, May 1993; *Control: Theory and Adv. Tech.*, **10** (1994), 873-892.

3. H.T. Banks and R.C. Smith, Active control of acoustic pressure fields using smart material technologies, ICASE Rep. 93-31, (June, 1993), NASA Langley Res. Ctr., Hampton, VA; in *Flow Control* (M. Gunzberger, ed.), Springer Verlag, New York, 1995, pp. 1-33.

4. H.T. Banks, K. Ito and Y. Wang, Well posedness for damped second order systems with unbounded input operators, CRSC-TR93-10, June, 1993; *Differential and Integral Equations*, **8** (1995), 587-606.

5. H.T. Banks, K. Black and B. Fitzpatrick, A report on the issues in groundwater modeling, CRSC-TR93-11, July 1993;

6. H.T. Banks and R.C. Smith, Feedback control of noise in a 2-D nonlinear structural acoustics model, CRSC-TR93-14, August 1993; *Discrete and Continuous Dynamical Systems*, **1** (1995), 119-149.

7. H.T. Banks and C.A. Smith, Modeling and identification of material parameters in coupled torsion and bending, CRSC-TR93-15, October 1993; *Math. and Computer Modeling*, **18** (1993), 1-19.

8. H.T. Banks and Y. Wang, Damage detection and characterization in smart material structures, CRSC-TR93-17, November 1993; in *Control and Estimation of Distributed Parameter Systems; Nonlinear Phenomena*, Birkhäuser ISNM, **118** (1994), pp. 21-43.

9. H.T. Banks, D.E. Brown, V.L. Metcalf, R.J. Silcox, R.C. Smith, and Y. Wang, A PDE-based methodology for modeling, parameter estimation, and feedback control in structural and structural acoustic systems , CRSC-TR94-1, January 1994; in *Mathematics and Control in Smart Structures*, SPIE, 1994, pp. 311-320.

10. H.T. Banks and Y. Wang, Distributed parameter system models for damage detection and location in smart material structures, in *Mathematics and Control in Smart Structures*, SPIE, 1994, pp. 199-208.

11. H.T. Banks and R.C. Smith, Noise control in a 3-D structural acoustic system: numerical simulations, CRSC-TR94-2, February 1994; in *Intelligent Materials* (C.A. Rogers,ed.), Technomics Publ. Co., Lancaster, PA, 1994, pp. 128-139.

12. H.T. Banks, R.C. Smith and Y. Wang, Vibration suppression with approximate finite dimensional compensators for distributed systems; Computational methods and experimental results , CRSC-TR94-3, February 1994; in *Intelligent Materials* (C.A. Rogers, ed.), Technomics Publ. Co., Lancaster, PA 1994, pp. 140-154.

13. H.T. Banks, M.A. Demetriou and R.C. Smith, Robust output feedback control in a 2-D structural acoustic model with piezoceramic actuators , in *Intellegent Materials* (C.A. Rogers, ed.), Technomics Publ. Co., Lancaster, PA 1994, pp. 109-127.

14. K. Black, A Petrov-Galerkin spectral element technique for porous media flow, *Computers and Mathematics with Applications*, E.Y. Rodin, ed., to appear.

15. K. Black, A Lanczos-Tau spectral element method, *J. of Scientific Computing*, submitted.

16. K. Ito, H.T. Tran, and J.S. Scroggs, Mathematical issues in optimal design of a vapor transport reactor, *Flow Control*, ed. by M. Gunzberger, Springer-Verlag, New York, 1995, pp. 197-218.

17. K. Ito, H.T. Tran, and J.S. Scroggs, Optimal control of thermally coupled Navier-Stokes equations, *SIAM J. Control and Optim.*, submitted.

18. K. Ito and K. Kunisch, Augmented Lagrangian-SQP methods in Hilbert spaces and applications to control in the coefficients problems, *SIAM J. Optim.*, to appear.

19. K. Ito and K. Kunisch, Augmented Lagrangian-SQP methods for a class of semilinear elliptic control problems, *SIAM J. Control and Optim.*, submitted.

20. K. Ito and K. Kunisch, Augmented Lagrangian methods for nonsmooth, convex optimizations in Hilbert spaces, *Applied Math. Optim.*, submitted.

21. H.T. Banks and K. Ito, Structural actuator control of fluid/structure interactions, Proc. 33rd IEEE Conf on Decision and Control, Dec., 1994, pp. 283-288.

22. H.T. Banks, B. Fitzpatrick and Yue Zhang, Estimation of distributed individual rates from aggregate population data, CRSC-TR94-13, Sept 1994; Proc. Conf on Differential Eqns, to appear.

23. H.T. Banks, S.L. Keeling and R.J. Silcox, Active control of propeller induces noise fields, CRSC-TR94-16, October, 1994.

24. H.T. Banks, D.S. Gilliam and V.I. Shubov, Well-posedness for a one dimensional nonlinear beam, CRSC-TR94-18, October, 1994; in *Computation and Control IV*, Birkhäuser, 1995, pp.1-21.

25. H.T. Banks and K. Ito, Approximation in LQR problems for infinite dimensional systems with unbounded input operators, CRSC-TR94-22, November, 1994; in *J. Math. Systems, Estimation and Control*, to appear.

26. H.T. Banks and R.C. Smith, The modeling and approximation of a structural acoustics problem in a hard-walled cylindrical domain, CRSC-TR94-26, December, 1994; appeared as the Chapter: Numerical Techniques for Simulation, Parameter Estimation and Noise Control in Structural Acoustics Systems, in *Dynamics and Control of Distributed Systems* (ed. H.S. Tzou and L.A. Bergman) Cambridge University Press, 1995.

27. H.T. Banks, R.C. Smith and Y. Wang, Modeling and parameter estimation for an imperfectly clamped plate, CRSC-TR95-2, January, 1995; in *Computation and Control IV*, Birkhäuser, 1995, pp. 23-42.

28. H.T. Banks, D.J. Inman, D.J. Leo, and Y. Wang, An experimentally validated damage detection theory in smart structures, CRSC-TR95-7, January, 1995; *ASME J. Sound and Vibration*, to appear.

29. H.T. Banks, M.A. Demetriou, R.C. Smith, Computational studies on the robustness of the $H_\infty$ feedback control in a 2-D structural acoustic model with periodic excitation, CRSC-TR95-12, March, 1995; *Intl. J. Nonlinear and Robust Control*, to appear.

30. H.T. Banks, M.A. Demetriou, R.C. Smith, Inverse problems in smart material structures, CRSC-TR95-13, March, 1995; *J. Inverse and Ill-posed Problems*, submitted.

31. H.T. Banks, J. Scroggs, K. Ito, S. Ravindran, H. Tran, K. Bachmann, and R. Castleberry, High pressure vapor transport of $ZnGeP_2$: I. parameter evaluation, in *International Symposium Experimental Methods for Microgravity Materials Science*, TMS, February 1995, p. to appear.

32. H.T. Banks, J. Scroggs, K. Ito, S. Ravindran, and H. Tran, High pressure vapor transport of $ZnGeP_2$: II. three-dimensional simulation of gasdynamics under microgravity, CRSC-TR95-15, April, 1995; in *International Symposium Experimental Methods for Microgravity Materials Science*, TMS, February 1995, p. to appear.

33. H.T. Banks and R.C. Smith, Implementation issues regarding PDE-based controllers - control of transient and periodic plate vibrations, CRSC-TR95-16, April, 1995.

34. K. Ito and S. Kang, Chosan University, Korea, A dissipative feedback control synthesis for systems arising in fluid dynamics, *SIAM J. Control & Optim*, 32 (1994), 831-854.

35. K. Ito and M. Desai, Optimal Control of Navier-Stokes equations, *SIAM J. Control & Optim.*, 32 (1994), 1428-1446.

36. K. Ito and W. Fang, University of West Virginia, Reconstruction of semiconductor doping profile from LBIC image, *SIAM J. Applied Mathematics*, (1994), 1067-1082.

37. K. Ito and R.H. Fabiano, Texas A & M, An approximation framework for equations in linear viscoelasticity with strongly singular kernels, *Quarterly of Applied Mathematics*, 52 (1994), 65-81.

38. K. Ito and F. Kappel, University of Graz, Austria, Approximation of semilinear Cauchy problems, *J. Nonlinear Analysis*, TMA, 24 (1995), 51-80.

39. K. Ito and K. Kunisch, Technical University of Berlin, Maximizing robustness in nonlinear illposed inverse problem, *SIAM J. Control & Optim*, (1995), 643-666 .

40. K. Ito and K. Kunisch, Technical University of Berlin, On the injectivity of the coefficient-to-solution mapping for elliptic boundary value problems and its linearization, *J. Math. Anal. Appl.*, 188 (1994), 1040-1066.

41. K. Ito and J.A. Burns, Virginia Polytechnic Institute, On well-posedness of integro-differential equations in weighted $L^2$-spaces, *Differential and Integral Eqs*, 8 (1995), 627-646.

42. K. Ito and W. Fang, University of West Virginia, On the time-dependent drift-diffusion model for semiconductors, *J. Differential Equations*, 117 (1995), 345-280.

43. Boundary temperature control for thermally coupled Navier-Stokes equations, *Control Theory for Distributed Parameter Systems: Nonlinear Phenomena*, (ed. by W.Desch, F.Kappel and K.Kunisch), ISNM 118, Birkhäuser (1994), 211-230.

44. K. Ito, H.T. Tran and J.S. Scroggs, Mathematical issues in optimal design of a vapor transport reactor, *Flow Control*, ed. by M.D. Gunzburger, Vol 68, IMA Volumes in Math.Appl., Springer, (1995), 197-218.

45. K. Ito, H.T. Tran and J.S. Scroggs, Optimal control of thermally coupled Navier-Stokes equations, *Optimal Design and Control*, ed. by J. Borggaard, et.al) PSCT 19, Birkhäuser (1994), 199-214.

46. A semigroup formulation of nonlinear size-structured distributed rate population model (with F. Kappel and C. Wang), CRSC-TR94-4, March 1994; in *Control and Estimation of Distributed Parameter Systems: Nonlinear Phenomena*, Birkhäuser ISNM, **118**(1994),pp.1-19.

47. Parameter estimation in a structural acoustic system with fully nonlinear coupling conditions (with R.C. Smith), CRSC-TR94-8, May, 1994; *Mathematical and Computer Modelin*, to appear.

48. An $H_\infty$/minmax periodic control in a 2-D structural acoustic model with piezoceramic actuators (with M.A. Demetriou and R.C. Smith), CRSC-TR94-9, June, 1994; *IEEE Trans. Auto. Control*, to appear.

49. Gasdynamics and transport in a high-pressure reactor under microgravity conditions (with K. Ito, J.S. Scroggs, H.T. Tran, K.J. Bachmann, H. Castleberry, and S. Fiechter), Proc. 2nd IEEE Mediteranean Symp. on New Directions in Control and Automation, June 1994, pp. 427-433.

50. Experimental confirmation of a PDE-based approach to design of feedback controls (with R.C. Smith, D. Brown, R. Silcox, and V. Metcalf) ICASE Report 95-42, NASA Langley Research Center, May, 1995; *SIAM J. Control Opt.*, submitted.

51. Nonlinear elastomers: modeling and estimation (with N.J. Lybeck, B. Muñoz, and L. Yanyo), CRSC-TR95-19, May, 1995; *Proc. 3rd IEEE Mediteranean Symp. on New Directions in Control*, Limassol, Cyprus, July, 1995, Vol. 1, pp. 1-7.

52. The estimation of material and patch parameters in a PDE-based circular plate model (with D.E. Brown, V.L. Metcalf, R.J. Silcox, and R.C. Smith), CRSC-TR95-24, July, 1995; *J. Sound and Vibration*, submitted.

53. Global solvability for damped abstract nonlinear hyperbolic systems (with D.S. Gilliam and V.I. Shubov), CRSC-TR95-25, August, 1995; *Differential and Integral Equations*, to appear.

54. A mathematical framework for curved active constrained layer structures: well-posedness and approximation (with N.G. Medhin and Y. Zhang), CRSC-TR95-32, September, 1995; *Num. Functional Anal. & Opt.*, submitted.

55. A nonlinear Lax-Milgram lemma arising in the modeling of elastomers (with N.J. Lybeck), CRSC-TR95-37, November, 1995; *Nonlinear Partial Differential Equations, Collège de France Seminar*, Vol. 13, 1996, to appear.

56. Computational methods for estimation in the modeling of nonlinear elastomers (with N.J. Lybeck, M.J. Gaitens, B.C. Muñoz, and L.C. Yanyo), CRSC-TR95-40, December, 1995; *Kybernetika*, submitted.

57. $H^\infty$ control of noise in a 3-D structural acoustic system (with M. Demetriou and R.C. Smith), *Proc. 34th IEEE Conf. of Dec. and Control* (New Orleans), December, 1995, pp. 3719-3724.

58. A new approach in identification of dielectric constants (with Y. Wang and M. Buksas), *Proc. 34th IEEE Conf. on Decision and Control*, (New Orleans), December, 1995, pp. 3730-3733.

59. K. Ito and W. Fang, Global solutions of the time-dependent drift-diffusion semiconductor equations, *J. Differential Equations*, (1994) to appear.

60. K. Ito and W. Fang, Asymptotic behavior of the drift-diffusion semiconductor equations, *J. Differential Equations*, (1994) to appear.

61. K. Ito and W. Fang, One-dimensional hydrodynamic model for semiconductors by viscosity method, *Proc. International Conf. on Diff. Eqs.*, Claremont (1994), to appear.

62. K. Ito, F. Kappel, and J. Turi, On well-posedness of singular neutral equations in the state space $C$, *J. Differential Equations*, (1995) to appear.

63. K. Ito and W. Fang, 'Weak solutions to a one-dimensional hydrodynamic model of two carrier types for semiconductors, *J. Nonlinear Analysis*, TMA, (1995) to appear.

64. K. Ito and K. Morris, An approximation theory for solutions to operator Riccati equations for $H^\infty$ control, *SIAM J. Control & Optimization*, submitted.

65. K. Ito, Weak Solutions to the one-dimensional non-isentropic gas dynamics by the vanishing viscosity method, *Comm. PDE*, submitted.

66. K. Ito Boundary control problem for Navier Stokes equations, *SIAM J. Control & Optimization*, submitted.

67. K. Ito and W. Fang, On the inhomogeneous system of isentropic gas dynamics by viscosity method, submitted.

68. K. Ito and K. Kunisch, Estimation of the convection coefficient in elliptic equations, *SIAM J. Control & Optimization*, submitted.

69. K. Ito and Y. Yan, Viscous scalar conservation law with nonlinear flux feedback and attractor, *J. Nonlinear Analysis* , TMA, submitted.

70. J. Baumeister, M. A. Demetriou, I. G. Rosen, and W. Scondo, On-line Estimation for Infinite Dimensional Dynamical Systems, *SIAM J. Control and Optimization*, submitted, 1994.

71. H. T. Banks, M. A. Demetriou, and R. C. Smith, Adaptive Parameter Estimation in a 2-D Structural Acoustic Model with Piezoceramic Actuators, in *Proceedings of the 1994 American Control Conference*, (Baltimore, Maryland), June, 1994.

72. M. A. Demetriou and B. G. Fitzpatrick, On line estimation of stiffness in nonlinear beam models with piezoceramic actuators, in *Proc. of the 1995 ASME Fifteenth Biennial Conference on Mechanical Vibration and Noise & 1995 ASME Design Technical Conferences*, (Boston, Mass), September 17-21 1995.

73. M. A. Demetriou and B. G. Fitzpatrick, Results on the adaptive estimation of stiffness in nonlinear beam models, in *Proc. of the 3rd IEEE Mediterranean Symposium on New Directions in Control and Automation*, (Limassol, CYPRUS), Jyly 11-13 1995.

74. M. A. Demetriou, I. G. Rosen, and S. Reich, Model Reference Adaptive Control of Abstract Nonlinear Distributed Parameter Systems, in *Proceedings of the 1994 American Control Conference*, (Baltimore, Maryland), June, 1994.

75. M. Böem, M. A. Demetriou, I. G. Rosen, and S. Reich, Model Reference Adaptive Control of Distributed Parameter Systems, *SIAM, J. Control and Optimization*, submitted, 1994.

76. M. A. Demetriou and I. G. Rosen, Model Reference Adaptive Control of Abstract Hyperbolic Distributed Parameter Systems, in *Proceedings of the 32nd IEEE Conference on Decision and Control*, (San Antonio, Texas), December 14-16, 1993, invited session.

77. M. A. Demetriou, Model Reference Adaptive Control of Slowly-Time Varying Parabolic Distributed Parameter Systems, in *Proceedings of the 33rd IEEE Conference on Decision and Control*, (Lake Buena Vista, Florida), December 14-16, 1994, invited session.

78. M. A. Demetriou and K. Ito, An adaptive controller for infinite dimensional dynamical systems, in *Proceedings of the 34rd IEEE Conference on Decision and Control*, (New Orleans, Louisiana), December 13-15, 1995.

79. M. A. Demetriou and K. Ito, A class of robust adaptive controllers for infinite dimensional dynamical systems, *SIAM Journal on Control and Optimization*, 1995, submitted.

80. M. A. Demetriou and B. G. Fitzpatrick, A change detection scheme for a nonlinear beam model, *Kybernetika*, 1995, submitted for consideration in a special issue on New Directions in Complex Systems for Control and Automation.

81. M. A. Demetriou, Fault diagnosis for a parabolic distributed parameter system, in *Proceedings of the 13th World Congress, International Federation of Automatic Control*, (San Francisco, California), July 1-5, 1996.

82. L. S. Hou, S. S. Ravindran and Y. Yan, Numerical Solutions of Optimal Distributed Control Problems for Incompressible Flows, *International Journal on Numerical Methods for Fluids*, submitted.

83. K. ITO and S. S. Ravindran, Optimal Control of Thermally Coupled Navier-Stokes Equations,*Proceedings of the 34th Conference in Decision and Control*, IEEE, 1995.

84. S. S. Ravindran, Optimal Electromagnetic Control of Turbulence: Analysis, Approximation and Computation, *Computers & Mathematics with Applications*, submitted.

85. Max D. Gunzburger, L.S. Hou, S. S. Ravindran and J. C. Turner, Analysis and Approximation of Optimal Control Problems with Nonlinear Constraints, *Proceedings of the 33rd Conference in Decision and Control*, IEEE, 1994, pp. 299-304.

86. L. S. Hou and S. S. Ravindran, Computations of Boundary Optimal Control Problems for an Electrically Conducting Fluid, *Journal of Computational Physics*, submitted.

87. L. S. Hou and S. S. Ravindran, Finite Element Approximation for Optimal Control of Electrically Conducting Fluids, *Proc. of Symposia in Applied Mathematics*, V. 48, 1994, pp305-309.

88. Max D. Gunzburger, L.S. Hou and S. S. Ravindran, Finite Element Approximation of Some Optimal Control, *Numer. Math*, submitted.

89. S. S. Ravindran, Electromagnetic Control for Fluid Flows, *Optimal Control of Viscous Flows*, S. S. Sritharan (Ed.), Frontiers in Applied Mathematics, SIAM, 1995.

90. N.J. Lybeck and K.L. Bowers, The Sinc-Galerkin Schwarz alternating method for Poisson's equation, in *Computation and Control IV*, (K. Bowers and J. Lund, ed.), Proc. Fourth Bozeman Conf., Birkhäuser Boston, Inc., 247–258, 1995.

91. N.J. Lybeck and K.L. Bowers, Domain decomposition in conjunction with sinc methods for Poisson's equation, *Numer. Meth. PDE's*, submitted.

92. A.C. Morlet, N.J. Lybeck, K.L. Bowers, Sinc domain decomposition methods II: the Schwarz alternating method, *IMA J. Numer. Anal.*, submitted.

93. A.C. Morlet, N.J. Lybeck, K.L. Bowers, Sinc domain decomposition methods I: the direct approach, *IMA J. Numer. Anal.*, submitted.

94. T.M Roberts and P.G. Petropoulos, Asymptotics and energy estimates for electromagnetic pulses in dispersive media, *J. Optical Society of America-A*, to appear.